Effect of impurity concentration on gamma-ray pulse shapes

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The capability of reconstructing the position of the interaction with a position resolution of 1-2 mm is a fundamental requirement for a γ-ray tracking detector [1]. Three dimensional position resolution (and energy of individual γ-ray interactions) is obtained by pulse shape analysis techniques. Pulse shape analysis is based on the fact that the features of the signal shapes are position dependent.

To determine the interaction locations with better accuracy than the segment size requires algorithms to decompose the signals in their individual components. These algorithms rely on a comparison between the observed pulse shape and a number of reference pulses from a basis of simulated signals. It is therefore very important that the basis of simulated pulses is a precise representation of the detector response. The aim of this work is to establish if the variation in the impurity concentration within the germanium crystal has a relevant effect on the detector signal shapes. In particular, the response of the GRETINA detector has been investigated.

The charge density left in the depleted region of the p-n junction is determined by the amount of acceptor atoms in the n-type crystal. This charge affects the electric field inside the detector and therefore the drift velocity of the charge carriers (which is not at saturation over the entire volume) and the shape of the induced charge signal. The distribution of the impurity concentration is not constant in the crystal and it can not be precisely measured. The manufacture measures the impurity concentration at the top and at the bottom of the germanium crystal. It is then assumed that the impurity concentration varies as a function of the distance (z) as $\rho=a+b\sqrt{z}$, where a and b are parameters calculated from the fit. This assumption is valid only in first approximation; moreover the impurity concentration may also vary radially.

The GRETINA triple-crystal module, made by Eurysis Measure, consists of tree coaxial crystals mounted in the same cryostat. Each crystal has a hexagonal shape (80 mm diameter, 90 mm length and 10 degree tapering) and is 36-fold segmented. From the manufacture we know that the impurity concentration varies between 0.45×10^{10} and 1.5×10^{10} atoms/cm^3 for crystal A, between 0.76×10^{10} and 1.2×10^{10} atoms/cm^3 for crystal B and between 0.83×10^{10} and 1.8×10^{10} atoms/cm^3 for crystal C.

Pulse shape simulations have been carried out to study variation of position sensitivity as a function of impurity concentration. Pulse shapes from the 36 segments of the detector are calculated using a dedicated program, which, given the electric field and the weighting potential inside the detector, calculates for singles-site interactions the drift path of the charge carriers and the charge signals induced at the electrodes during their motion.

In order to study the effect of impurity concentration on position sensitivity, the quantity χ^2 is defined as:

$$\chi^2_{ij} = \sum_m \sum_t \frac{[q_i(m,t) - q_j(m,t)]^2}{2\sigma^2}$$

where $q_{i,j}$ are the charge signals corresponding to the impurity density $\rho_{i,j}$, m is the segment number, t is the time and σ is the noise level, assumed to be constant (5 keV).

This quantity measures the amount by which two signals originated at the same position but for different impurity concentration differ relative to the noise.

If χ^2 is less than 1, the difference between the pulse shapes is less than the total noise contribution, i.e. the pulse shapes are indistinguishable, instead, if $\chi^2 \geq 1$ the pulse shapes can be distinguished. In the calculation χ^2 has been normalized so that $\chi^2 = 1$ corresponds to a position sensitivity of 1 mm.

Pulse shapes have been calculated for various impurity values (ρ_i) from zero to 1.4×10^{10} atoms/cm^3, and χ^2 has been calculated relative to a reference value (ρ_j) of 1.0×10^{10}. Fig. 1 shows χ^2 as a function of ρ. If the difference between ρ_i and ρ_j is less than 0.75×10^{10} atoms/cm^3 χ^2 is less than 1 and the signal shapes can not be distinguished. It can, therefore, be concluded that, since the range in the impurity concentration provided by the manufacturer is less than 0.75×10^{10} atoms/cm^3, our capability of reconstructing the interaction position with 1 mm position resolution, is not affected.

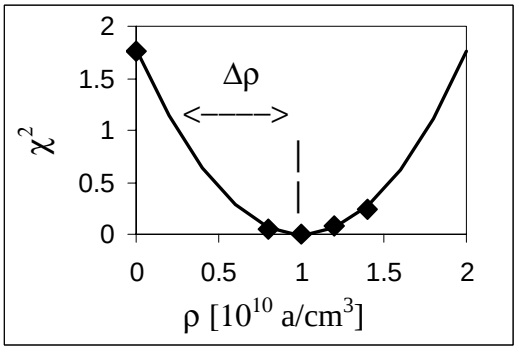

FIG. 1: Value of χ^2 as a function in impurity concentration. Δρ indicates the difference from a reference value of 1.0×10^{10} atoms/cm^3.

REFERENCES

[1] A Proposal for GRETINA, LBNL, June 2003.